

Population III stars: hidden or disappeared ?

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ABSTRACT

A Pop III/Pop II transition from massive to normal stars is predicted to occur when the metallicity of the star forming gas crosses the critical range $Z_{cr} = 10^{-5\pm1} Z_{\odot}$. To investigate the cosmic implications of such process we use numerical simulations which follow the evolution, metal enrichment and energy deposition of both Pop III and Pop II stars. We find that: (i) due to inefficient heavy element transport by outflows and slow "genetic" transmission during hierarchical growth, large fluctuations around the average metallicity arise; as a result Pop III star formation continues down to $z = 2.5$, but at a low peak rate of $10^{-5} M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$ occurring at $z \approx 6$ (about 10^{-4} of the Pop II one); (ii) Pop III star formation proceeds in a "inside-out" mode in which formation sites are progressively confined at the periphery of collapsed structures, where the low gas density and correspondingly long free-fall timescales result in a very inefficient astration. These conclusions strongly encourage deep searches for pristine star formation sites at moderate ($2 < z < 5$) redshifts where metal free stars are likely to be hidden.

Key words: galaxies: formation - cosmology: theory - cosmology: observations - intergalactic medium

1 INTRODUCTION

The physical conditions in primordial star-forming regions appear to systematically favor the formation of very massive stars. This is due to the combined effect of the larger gas fragmentation scale and accretion rate, and the very limited opacity. On the other hand, observations of present-day stellar populations (Pop II/I stars) show that stars form according to a Salpeter Initial Mass Function (IMF) with a characteristic mass of $\approx 1 M_{\odot}$, below which the IMF flattens. Thus, unless the current picture of primordial star formation is lacking in some fundamental ingredient, a transition between these two modes of star formation must have occurred at some time during cosmic evolution.

What are the physical drivers of such transition ? Since the early study by Yoshii & Sabano (1980), gas metallicity has been suspected to play a key role. This idea has been later on expanded and substantiated by a number of detailed studies (Omukai 2000; Bromm et al. 2001; Schneider et al. 2002, 2003). The emerging physical interpretation states that the fragmentation properties of the collapsing clouds change as the mean metallicity of the gas increases above a critical threshold, $Z_{cr} = 10^{-5\pm1} Z_{\odot}$. The characteristic masses of protostellar gas clouds with $Z < Z_{cr}$ are predicted to be relatively large ($> 100 M_{\odot}$), whereas in clouds with $Z > Z_{cr}$ lower characteristic masses can be

formed. Within the critical metallicity range, low-mass gas clouds can form if a sufficient amount of metals are depleted onto dust grains, which provide an additional efficient cooling channel at high density (Schneider et al. 2003; 2006a; Omukai et al. 2005; Omukai & Tsuribe 2006). According to this view, the formation of Pop III stars (defined as those with $Z < Z_{cr}$) is regulated by the rate at which heavy elements are produced and mixed in the gas surrounding the first star-forming regions (*chemical feedback*).

In principle, Pop III stars can continue to form until late epochs, provided that gas pockets of sufficiently low metallicity can be preserved during cosmic evolution. This condition can be met for newly formed halos that either (i) gain their gas from regions not yet polluted by outflows from nearby star forming galaxies, or (ii) have progenitors in which star formation has not occurred or was suppressed (Ciardi & Ferrara 2005). Thus, chemical feedback can act via two physically different channels, involving either the transport of metals by outflows or in a "genetic" form, *i.e.* inheriting metals from the parent sub-halos (Schneider et al. 2006b).

Scannapieco, Schneider & Ferrara (2003, SSF) studied the relative importance of the outflow channel, finding that metal transport is generally inefficient; as a consequence the transition epoch is extended in time, coeval Pop III and Pop II star formation occurs, and Pop III stars con-

tinue to form down to $z \lesssim 5$. Similar conclusions are reached by Furlanetto & Loeb (2005). Analytic models (Mackey, Bromm & Hernquist 2003) and high-resolution numerical simulations (Yoshida, Bromm & Hernquist 2004) show that if most of the early generation stars die as pair-instability supernovae, the *volume-averaged* IGM metallicity will quickly reach $Z = 10^{-4} Z_{\odot}$ by $z \approx 15 - 20$. However, as shown by SSF and confirmed here, this condition does not guarantee a self-termination of massive Pop III star formation, due to the highly inhomogeneous metal distribution.

Additional complications come from the effects of radiative feedback (Ricotti, Gnedin & Shull 2002; Machacek, Bryan, Abel 2003; Omukai & Yoshii 2003; Yoshida et al. 2003; Susa & Umemura 2006), HD chemistry (Nagakura & Omukai 2005; Greif & Bromm 2006; Johnson & Bromm 2006; Yoshida et al. 2007) and radiative transfer (Ciardi, Ferrara & Abel 2000; Ricotti, Gnedin & Shull 2001; Kitayama et al. 2001). These are generally found to be important for mini-halos ($T_{\text{vir}} < 10^4$ K), or under physical conditions not relevant for this study.

Although the above studies find difficult to rapidly suppress the formation of Pop III stars, this common wisdom has to face the fact that no metal-free stars have yet been found by surveys of metal-poor stars of the Milky Way halo (Cayrel et al. 2004; Beers & Christlieb 2005; Tumlinson, Venkatesan, Shull 2004; Tumlinson 2006; Daigne et al. 2006; Salvadori, Schneider & Ferrara 2007). Alternative probes as (i) the apparent excess in the cosmic near-infrared background (Salvaterra & Ferrara 2003; Santos, Bromm & Kamionkowski 2002; Salvaterra et al. 2006; Kashlinsky et al. 2006a,b), (ii) the equivalent width distributions of high- z Ly α emitters (Malhotra & Rhoads 2002; Dawson et al. 2004), (iii) the He II 1640Å line in composite spectra of LBGs (Shapley et al. 2003; Nagao et al. 2005) are yielding only tentative evidence for the presence of Pop III stars at $z < 9$.

The question then remains: are Pop III stars hidden (due to their very small statistical frequency or because they reside in yet unexplored environments) or did they disappear as a result of chemical feedback a long time ago? The aim of this Letter is an attempt to address this question.

2 NUMERICAL SIMULATIONS

For the present study we have performed a set of cosmological¹ simulations using the publicly available code GADGET² (Springel 2005) with an improved treatment of chemical enrichment as in Tornatore et al. (2007). For the present study, we have further implemented the possibility to assign different Initial Mass Functions (IMF) to each star forming particle, depending on the gas metallicity. In particular, for the purpose of this work, if $Z < Z_{\text{cr}}$, the adopted IMF is a Salpeter law with lower (upper) limit of $100M_{\odot}$ ($500M_{\odot}$); only stars in the pair-instability ($140M_{\odot} < M < 260M_{\odot}$) range contribute to metal enrichment (Heger &

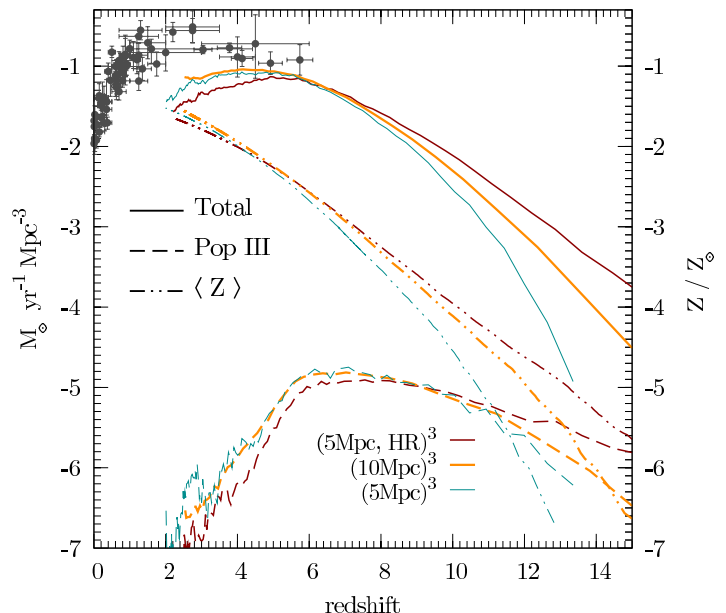


Figure 1. Predicted evolution of Pop II (solid lines) and Pop III (dashed) cosmic star formation rates, and mass-averaged metallicity (dot-dot-dashed). The results of the three different simulation runs described in the text are shown for each quantity. As a reference, low-redshift measurements (points) taken from Hopkins (2004) are reported.

Woosley 2002). If $Z \geq Z_{\text{cr}}$, we assume that the above limits are shifted to $0.1M_{\odot}$ ($100M_{\odot}$), respectively; stars above $40M_{\odot}$ end their lives as black holes swallowing their metals. In the following, we show results for $Z_{\text{cr}} = 10^{-4} Z_{\odot}$. These two populations, to which we will refer to as Pop III and Pop II stars respectively, differ also for their metal yield (i.e. the fraction of stellar mass transformed into metals), y , and explosion energy per unit mass of baryons going into stars, ϵ . For Pop III stars we follow Heger & Woosley (2002) and assume $y = 0.183$, $\epsilon = 3.5 \times 10^{16}$ erg g^{-1} ; for Pop II stars we adopt a metallicity-dependent value of y taken from Woosley & Weaver (1995) and $\epsilon = 3.4 \times 10^{15}$ erg g^{-1} . Consistently with the above yields, we follow the production and transport of six different metal species, namely: C, O, Mg, Si, S, Fe. In our simulations, the IMF depends on the value of the gas metallicity. Physically, the gas can be enriched by metals released by local stars or through winds powered by stars in nearby regions. Thus, the IMF is determined according to the SPH-smoothed value³ rather than on the intrinsic particle metallicity. For the purpose of this work, we have chosen to simulate a (comoving) volume of $L = 10h^{-1}$ Mpc with $N_p = 2 \times 256^3$ (dark+baryonic) particles, corresponding to a dark matter (baryonic) particle mass of $M_p = 3.62 \times 10^6 h^{-1} M_{\odot}$ ($6.83 \times 10^5 h^{-1} M_{\odot}$); the corresponding force resolution is 2 kpc. Our resolution does not allow to track the formation of mini-halos, whose stellar contribution remains very uncertain due to radiative feedback effects (Haiman & Bryan 2006; Susa & Umemura 2006; Ahn & Shapiro 2007).

The computation is initialized at $z = 99$ and carried

¹ Throughout the paper, we adopt a Λ CDM cosmological model with parameters $\Omega_M = 0.26$, $\Omega_{\Lambda} = 0.74$, $h = 0.73$, $\Omega_b = 0.041$, $n = 1$ and $\sigma_8 = 0.8$, in agreement with the 3-yr WMAP results (Spergel et al. 2006).

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³ The Z-smoothing is calculated normalizing the kernel in a sub-region of the sph volume (here 0.2 of the sph length), independently of the number of neighbors found.

on until $z = 2.5$. In order to check the convergence of the results, we have run two additional simulations with $L = 5h^{-1}$ Mpc and $N_p = 2 \times (256^3, 128^3)$, the latter one having the same particle mass as in the reference run.

The gas photo-ionization and heating rates are calculated at equilibrium with a background ionizing radiation due to the combined contribution of galaxies and quasars, taken from Haardt & Madau (1996), shifted so that the intensity at 1 Ryd is $J_\nu = 0.3 \times 10^{-21}$ erg s $^{-1}$ Hz $^{-1}$, in agreement with Bolton et al. (2005). Gas cools according to the cooling function given by Sutherland & Dopita (1993), corrected for both helium and hydrogen photoionization; because metal photoionization is not followed explicitly, the cooling might be somewhat overestimated. Supernova winds are treated as in the original model by Springel & Hernquist (2003); however, for simplicity and because the mass load and kinetic energy fraction are unknown parameters, we have given the winds from both population an initial velocity $v_w = 500$ km s $^{-1}$, which appears to be consistent with that derived from observations of high- z starburst galaxies (Adelberger et al. 2003; Shapley et al. 2003). Wind particles are temporarily hydrodynamically decoupled until either (i) they have moved by a traveling length $\lambda = 2$ kpc, or (ii) their density has decreased below 0.5 times the star formation density threshold ($n_\star = 0.1$ cm $^{-3}$). The metals are donated by star particles to the surrounding gas ones using a SPH kernel as described in Tornatore et al. (2007).

3 RESULTS

Our simulation outputs contain a large number of useful information concerning the mode (Pop III or Pop II) of star formation and the source of metals associated to each particle. In addition, we can recover if heavy elements have been produced *in situ* or transported to that location by outflows.

We start the analysis of the simulation outputs by reconstructing the evolution of Pop II and Pop III star formation rates (SFR) and the corresponding evolution of the mass-averaged metallicity, $\langle Z \rangle$, due to the dispersal of heavy elements produced by these stars. These are shown by the curves in Fig. 1. Star formation begins very early ($z \gtrsim 15$) for both populations. At these high redshifts, though, there are considerable uncertainties in the rates due to numerical resolution effects, as gathered from a comparison among the three runs reported in Fig. 1. In general, decreasing the resolution leads to an underestimate of the SFR at high redshift; smaller volumes, instead, miss the activity at later (and more easily observable) epochs. Note, however, that the scatter in the PopIII/PopII SFR ratio remains $< 20 - 30\%$ independent of resolution. For this reason we consider $L = 10h^{-1}$ Mpc, $N_p = 2 \times 256^3$ as our fiducial run.

The gas mass enriched to $Z > Z_{\text{cr}}$ by a single Pop III star is so large that Pop II stars are always the dominant star formation mode (apart the very first event): at $z = 14$ only about 1% of the stars in the universe are born in formation sites where $Z < Z_{\text{cr}}$, and hence producing Pop III stars. Such ratio steadily decreases reaching $\approx 10^{-4}$ at $z = 6$ and rapidly dropping afterwards.

We pause to outline two important points. First, and in agreement with previous findings by SSF and Schneider et al. 2006, Pop III stars continue to form well beyond $z = 10$,

the epoch at which $\langle Z \rangle > Z_{\text{cr}}$, at non-negligible rates: for example, at $z = 5$, the SFR integrated over the corresponding Hubble time would yield a Pop III stellar density of $\Omega_{\text{III}} \approx 2 \times 10^{-6} \Omega_b$. This does not come as a surprise if we note that, due to the highly inhomogeneous nature of metal enrichment (see below), relatively pristine regions survive for several Gyr; these are the host environment for Pop III formation sites. The second point to note is that, in addition to chemical feedback, the suppression of Pop III star formation is also caused by the IGM photo-heating due to reionization, which in our simulation occurs at $z \approx 7$. In fact, the associated increase of the Jeans (or more precisely, filtering) scale inhibits the collapse of low mass halos which are more likely to be relatively uncontaminated (Schneider et al. 2006) with respect to larger ones which are genetically polluted by their merging progenitors.

To make further progress, let us look at the relative spatial distribution of metals and Pop III star forming sites. In Fig. 2 we show 500 kpc thick slices through the simulation volume at three different redshifts $z = 3, 5, 10$. The maps represent the spatial distribution at these three epochs of $\langle Z \rangle$ (left panels) and the fractional gas metallicity contributed by Pop III stars, $R_3 = M_{Z,\text{III}} / (M_{Z,\text{III}} + M_{Z,\text{II}})$; by construction, $0 < R_3 < 1$. At $z = 10$, the volume filling factor of metals is small, with only a few isolated star-forming regions. The most active sites are rapidly making the transition to Pop II star formation mode, as reflected by the fact that $R_3 \ll 1$ within the largest metal enriched patches; it is only in the smallest and most recently polluted regions that Pop III enrichment dominates ($R_3 \approx 1$). As evolution proceeds, the metal bubbles tend to grow around the most ancient star forming sites, propagating in an inside-out fashion⁴. The metallicity structure of the bubbles is such that their interior is dominated by Pop II metals, with Pop III stars confined in the outermost boundary. Thus, the formation of Pop III stars is forced to move away from the sites where the first generation of stars formed. In addition, it becomes less intense as it migrates away from the density peaks that harbored the first stars. The termination of the Pop III era occurs when all regions with a (total) density above the star formation threshold (assumed to be $n_\star = 0.1$ cm $^{-3}$) reach the critical metallicity.

This evolution reverses the naively expected age-metallicity relation: at any given redshift there are (almost) metal-free stars that are *younger* than their enriched counterparts. Quantitatively, at $z = 10$ we find that of the enriched (*i.e.* with $Z > 0$) gas mass, a fraction of ≈ 0.26 (≈ 0.26) is purely polluted by Pop II (Pop III) stars. These figures change to ≈ 0.46 (≈ 0.03) at $z = 5$ and to ≈ 0.7 (≈ 0.01) at $z = 3$. At all redshifts the remaining enriched gas has a mixed Pop III/Pop II composition. The overall conclusion is that below $z \approx 9$ most of the gas has been enriched only through Pop II supernovae.

Fig. 3 presents the mass-averaged metallicity color-coded phase diagram of the gas in the simulated volume. Each pixel value represents the mean temperature and $\langle Z \rangle$ of the particles within a given mass-overdensity range. There we recognize the arch-shaped feature ($T \approx 10^4$ K) charac-

⁴ Note that, due to projection effects, the bubble interiors are contaminated by foreground Pop III enriched pockets.

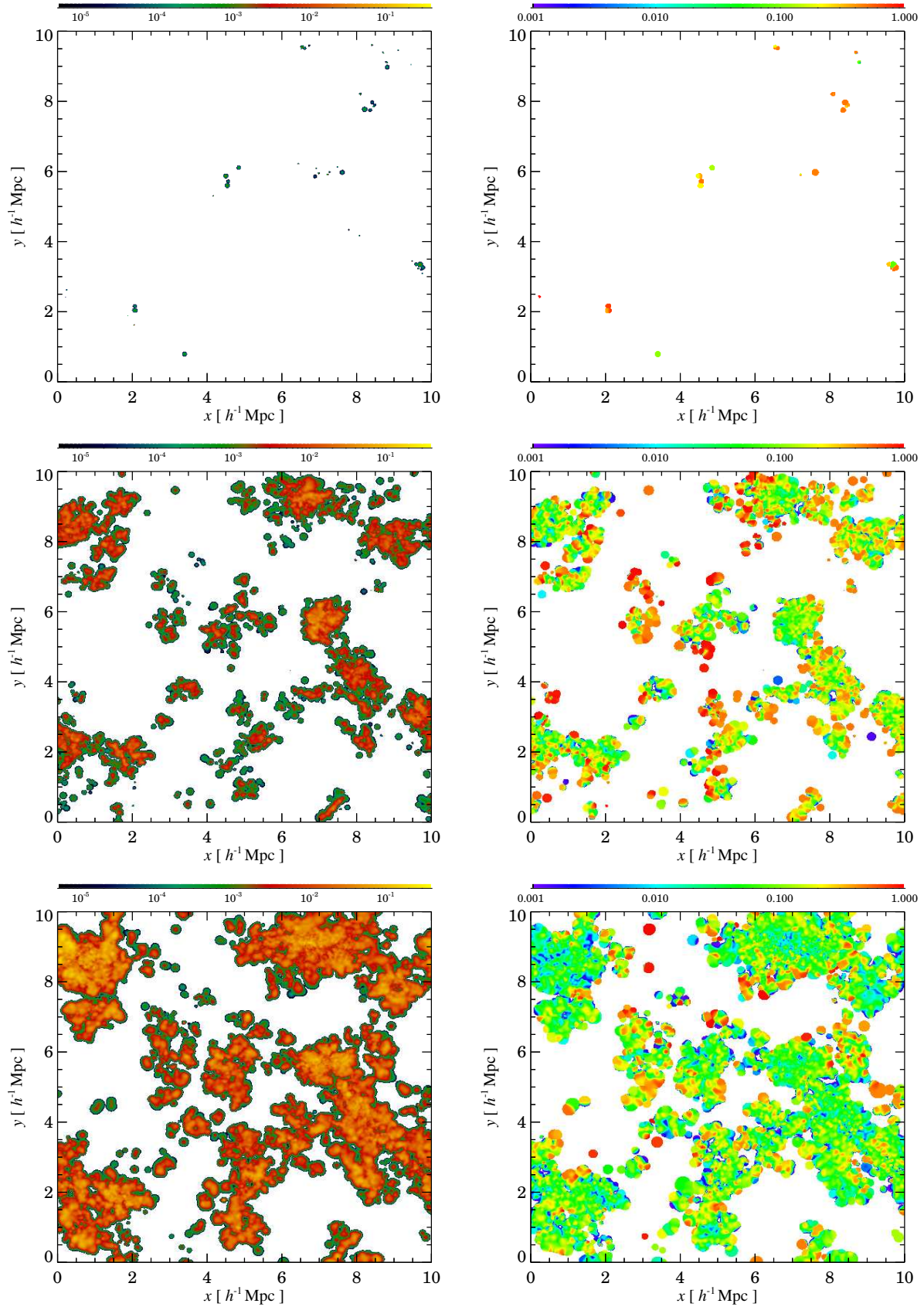


Figure 2. Maps resulting from the projection of 500 kpc-thick slices through the simulation volume of total mass-averaged metallicity, $\langle Z \rangle$ (left panels) and fractional gas metallicity contributed by Pop III stars, $R_3 = M_{Z,III}/(M_{Z,III} + M_{Z,II})$ (right) for three selected redshifts, $z = 10, 5, 3$ from top to bottom, respectively.

terizing low density IGM (i.e. the Ly α forest) whose thermal budget results from the balance between photo-heating and adiabatic cooling. The hot $T > 10^{4.5}$ K, tenuous (over-density $\Delta = \rho_c/\langle\rho\rangle < 10$) phase has two distinct origins as indicated by its metallicity: (i) gas shocked by galactic outflows ($Z > 10^{-4}Z_\odot$), and (ii) gas virializing in forming galaxies ($Z < 10^{-4}Z_\odot$): galaxies forming out of this gas can potentially form Pop III stars. The most relevant region of the phase plane for this study is the oblique branch found at overdensities $\Delta \gtrsim 3 \times 10^2$. Most of this dense gas has $\langle Z \rangle \gg Z_{\text{cr}}$ and is located in active regions of Pop II star formation. However, a minor fraction of the gas has $\langle Z \rangle < Z_{\text{cr}}$ (region inside the rectangle in Fig. 3) and it is forming Pop III stars. The Pop III forming sites have densities only slightly above the critical threshold ($\Delta \approx 300$ at $z = 5$) and cool temperatures. As already pointed out, Pop III star formation is progressively confined into low density gas, i.e. the periphery of collapsing structures. The right panel of Fig. 3 further illustrates this point. Almost independently of redshift, Pop III stars tend to form on average in regions where $\langle Z \rangle \approx 0.1Z_{\text{cr}}$, although a considerable spread around such value is found.

4 CONCLUSIONS

The main finding of this study is that Pop III star formation can continue down to very low $z \approx 2.5$ thanks to the fact that, due to inefficient metal enrichment, pockets of almost pristine ($Z < Z_{\text{cr}}$) gas continue to exist. This confirms the results of previous semi-analytical models (SSF; Schneider et al. 2006). A general evolutionary picture emerges in which Pop III star formation starts in the highest density peaks of the cosmic density field which are then polluted by their metals and turn into Pop II sites, hence forcing Pop III star formation to migrate towards the outer, low-density environments. The inside-out propagating “Pop III-wave” stops when the environmental density has dropped below the star formation threshold, n_\star . Such segregation in regions of density slightly above n_\star causes Pop III star formation efficiency to remain low, due to the long free-fall and cooling timescales. This is at odd with semi-analytic models which generally assume a much higher (0.01-0.1) conversion efficiency of gas to Pop III stars. A more detailed comparison between numerical and semi-analytical approaches is deferred to future work. Pop III stars preferentially form in regions where the mass-averaged gas metallicity is $10^{-5}Z_\odot$, i.e. 10% of the critical metallicity value adopted here. Finally, we have checked the robustness of all these results against the uncertainties in the modeling of metal transport and diffusion, adopting different numerical schemes to describe these processes, as discussed in Tornatore et al. (2007).

The above findings are quite encouraging for searches of Pop III stars at moderate redshifts as it appears that rather than disappeared, these stars are hidden in the outskirts of collapsing structures. Thus, a non-negligible fraction of observable $z > 3$ objects may be powered by the radiative (Lyman- α emitters, Lyman Break Galaxies: SSF, Malhotra & Rhoads 2002; Dawson et al. 2004; Jimenez & Haiman 2006) or mechanical (pair-instability supernovae: Scannapieco et al. 2005) input of Pop III stars. On the

other hand, identifying nucleosynthetic signatures of Pop III stars appears extremely challenging, as only a tiny fraction (8×10^{-5}) of the baryons at $z = 3$ has been contaminated purely by Pop III metals. Alternative strategies based on the detection of extremely metal-poor stars in the Galactic halo face a similar difficulty in spotting truly second-generation stars (Salvadori et al. 2007). Thus, it is likely that robust identifications of metal-free stars at high redshift would be obtained for objects characterized by large ($> 10^3$ Å) Ly- α equivalent widths and/or strong HeII 1640 Å line. However, constraining the mass range, or even the IMF, of such stars on this basis is very difficult.

A final question remains on which physical mechanism dominates the chemical feedback: transport of metals by outflows or a “genetic” form, i.e. inheriting metals from the parent sub-halos. From the discussion above, it is clear that some fraction of the IGM is polluted by winds to high metallicity preventing it from subsequently forming Pop IIIs. At present, the role of the “genetic” transmission of metals can not be straightforwardly deduced from our study, as it requires a detailed investigation of the merging history and metallicity evolution of host halos which we defer to future work.

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⁵ www.arcetri.astro.it/science/cosmology

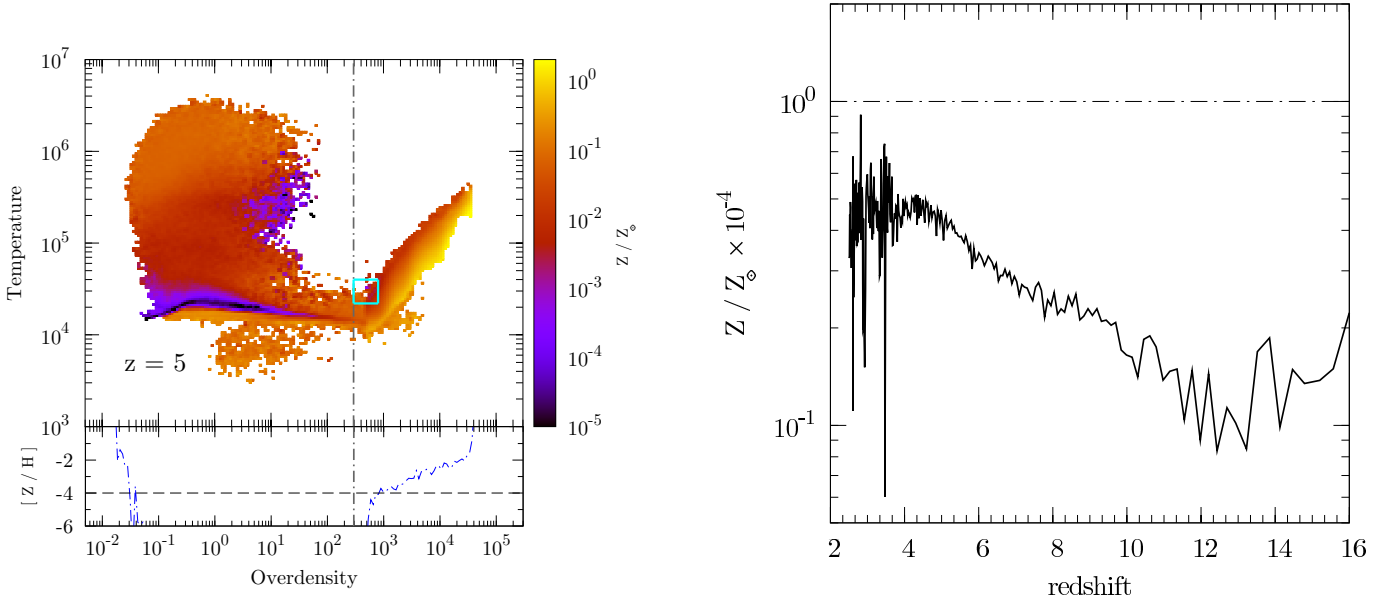


Figure 3. *Left:* Mass-averaged metallicity color-coded phase diagram of the gas in the simulated volume at $z = 5$. Each pixel value represents the $\langle Z \rangle$ of the particles within a given temperature-overdensity range. The dot-dashed vertical line indicates the star formation density threshold $n_* = 0.1 \text{ cm}^{-3}$. The rectangle indicates the area in which PopIII-forming particles are found. In the lower panel we plot the minimum metallicity found in each overdensity bin (also shown with a dashed line is the value $Z = Z_{\text{cr}}$); star forming particles having $Z < Z_{\text{cr}}$ are found in the range $300 < \rho_c / \langle \rho \rangle < 600$. *Right:* Mass-averaged mean metallicity of PopIII star forming sites as a function of redshift. The dot-dashed line is the value $Z = Z_{\text{cr}}$.

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